# The current status of DANCE: Dark matter Axion search with riNg Cavity Experiment

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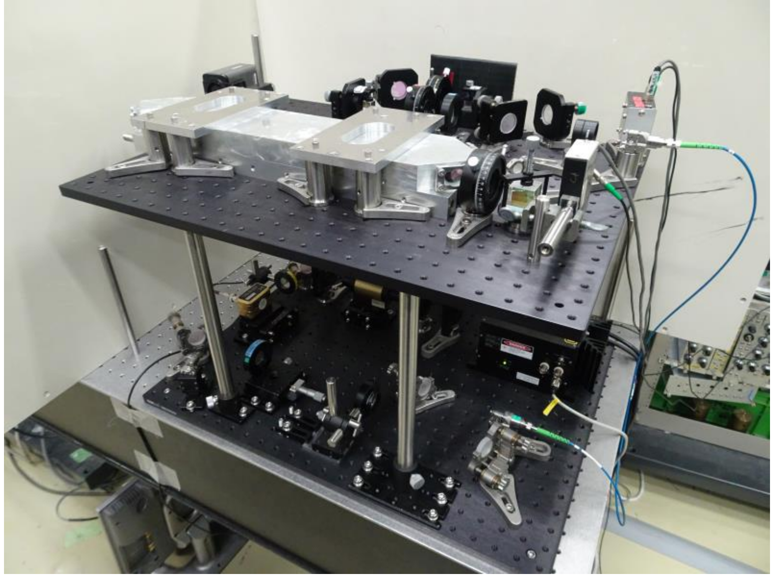
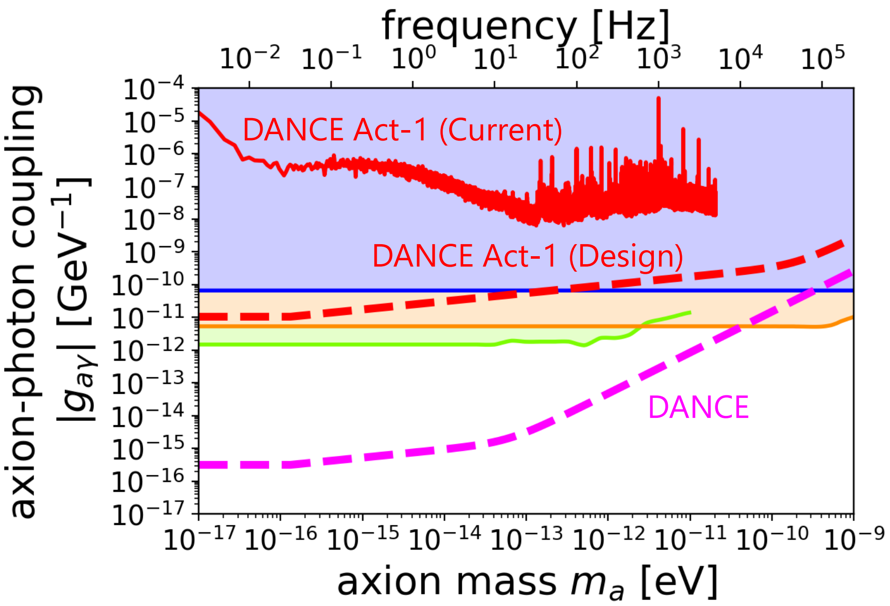
# Overview

- A new method to search for axion-like particles with a table-top experiment
  I. Obata, T. Fujita, Y. Michimura, [PRL 121, 161301 (2018)]
- DANCE: Dark matter Axion search with riNg Cavity Experiment
- Prototype experiment DANCE Act-1 is ongoing





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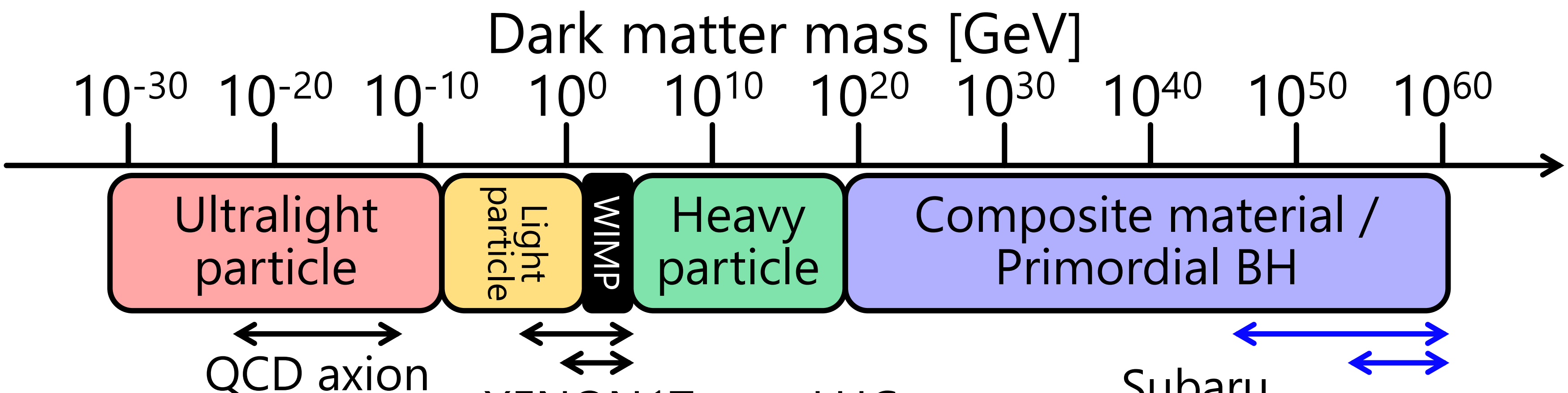
- Introduction
  - Axion
  - Previous researches
- Methods
  - Principle of DANCE
  - Experimental setups of DANCE
- Results
  - Performance evaluation of a cavity
  - Data analysis & Sensitivity
- Discussion & Future plans

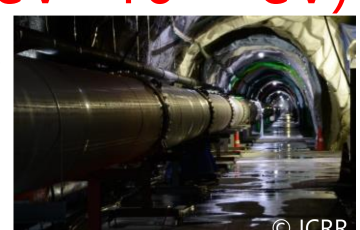
# Ultralight dark matter

- Dark matter has not been detected yet
- Need to search in wider mass range
- Ultralight dark matter search with laser interferometer is attracting attention




2.4 Hz - 2.4 kHz
($10^{-14}$ eV- $10^{-11}$ eV)

KAGRA




XENON1T

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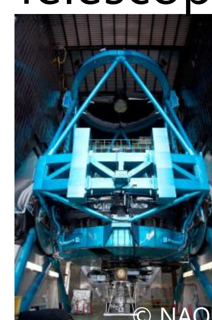
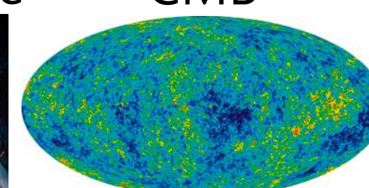
LHC


Subaru Telescope




CMB



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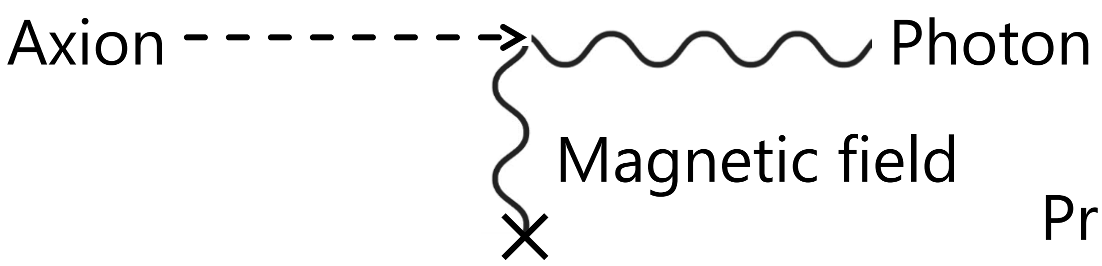
# Axion

- Hypothetical particles to solve the strong CP problem in QCD

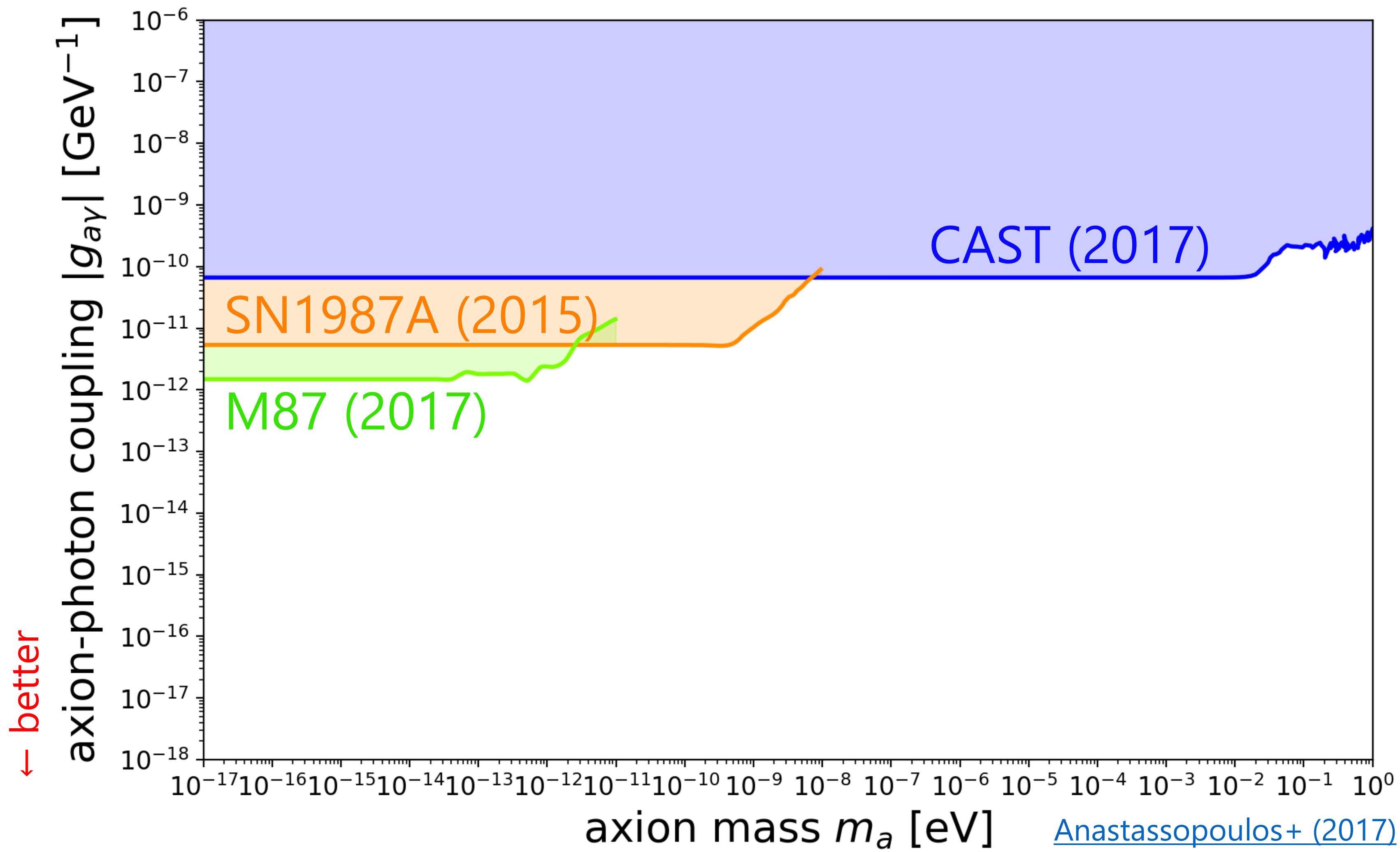
- Many kinds of axion-like particles (ALPs) are predicted by superstring theory
  - One of the candidates for dark matter

- Various methods of measuring axion-photon coupling, especially by using magnetic field, are proposed in many treatise




Primakoff effect

# Upper limits from previous researches




Anastassopoulos+ (2017)
Payez+ (2015)
Marsh+ (2017)

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# Rotation of linear polarization

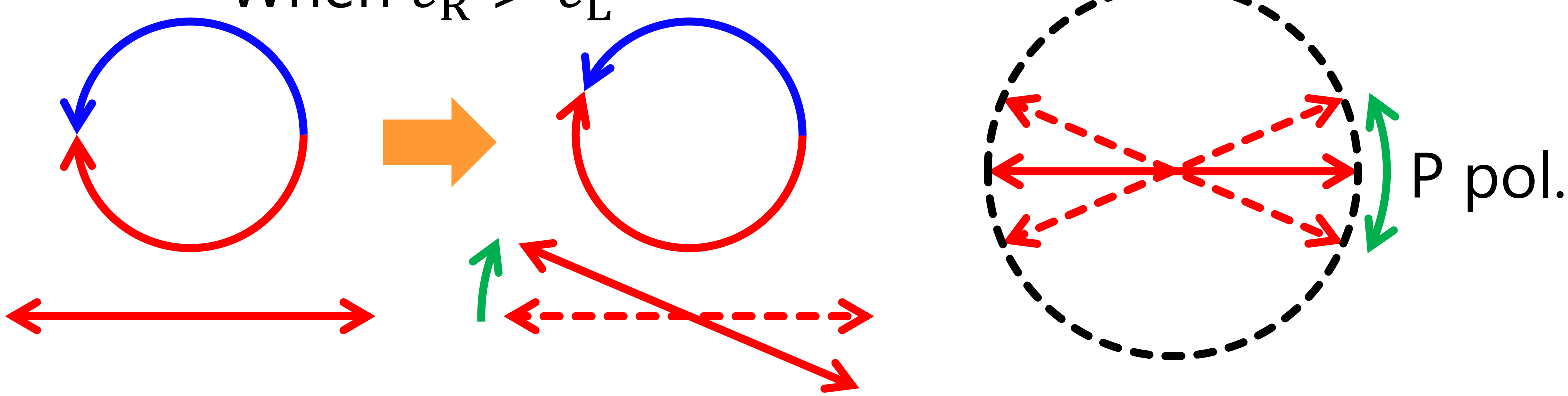
- Axion-photon coupling causes phase velocity difference between left- and right-handed photons

$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

Coupling constant　Axion field　Axion mass

- Phase velocity difference of circular polarizations makes linear polarization rotate

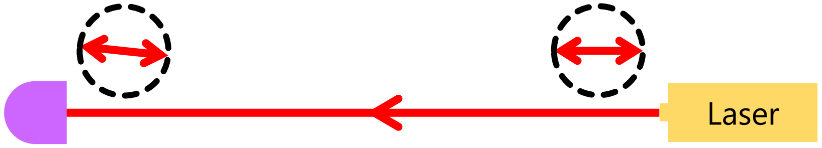
When $c_{\mathrm{R}} > c_{\mathrm{L}}$



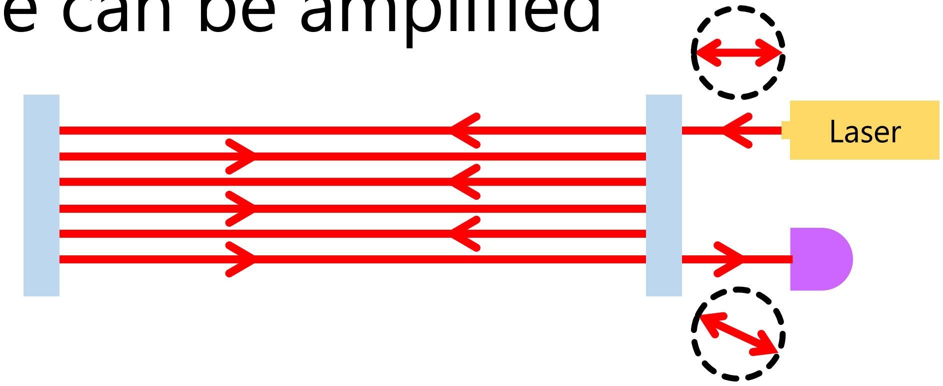
# Amplification of rotation angle

- We measure rotation angle of linear polarization caused by axion (if axion is DM)

- Rotation angle is too small to be observed without a cavity

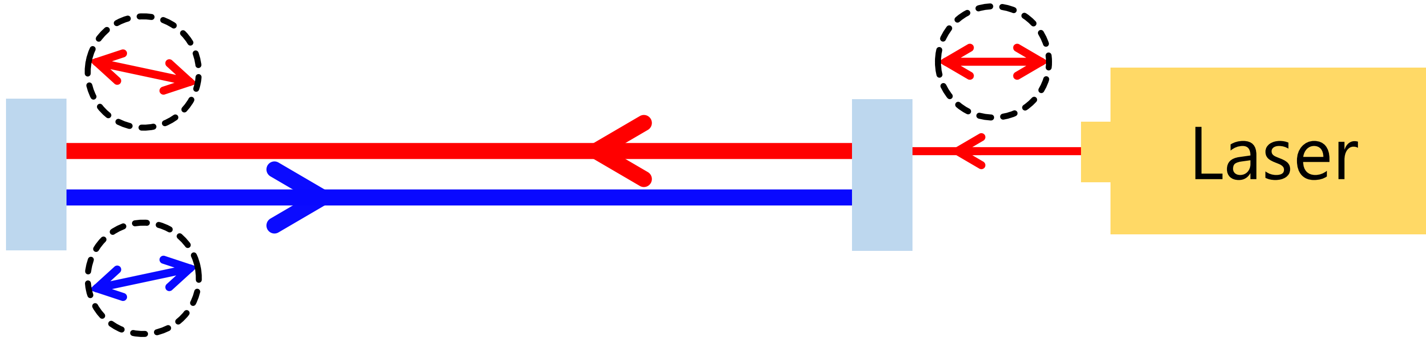



- Laser light runs between mirrors many times in a cavity
  → Rotation angle can be amplified



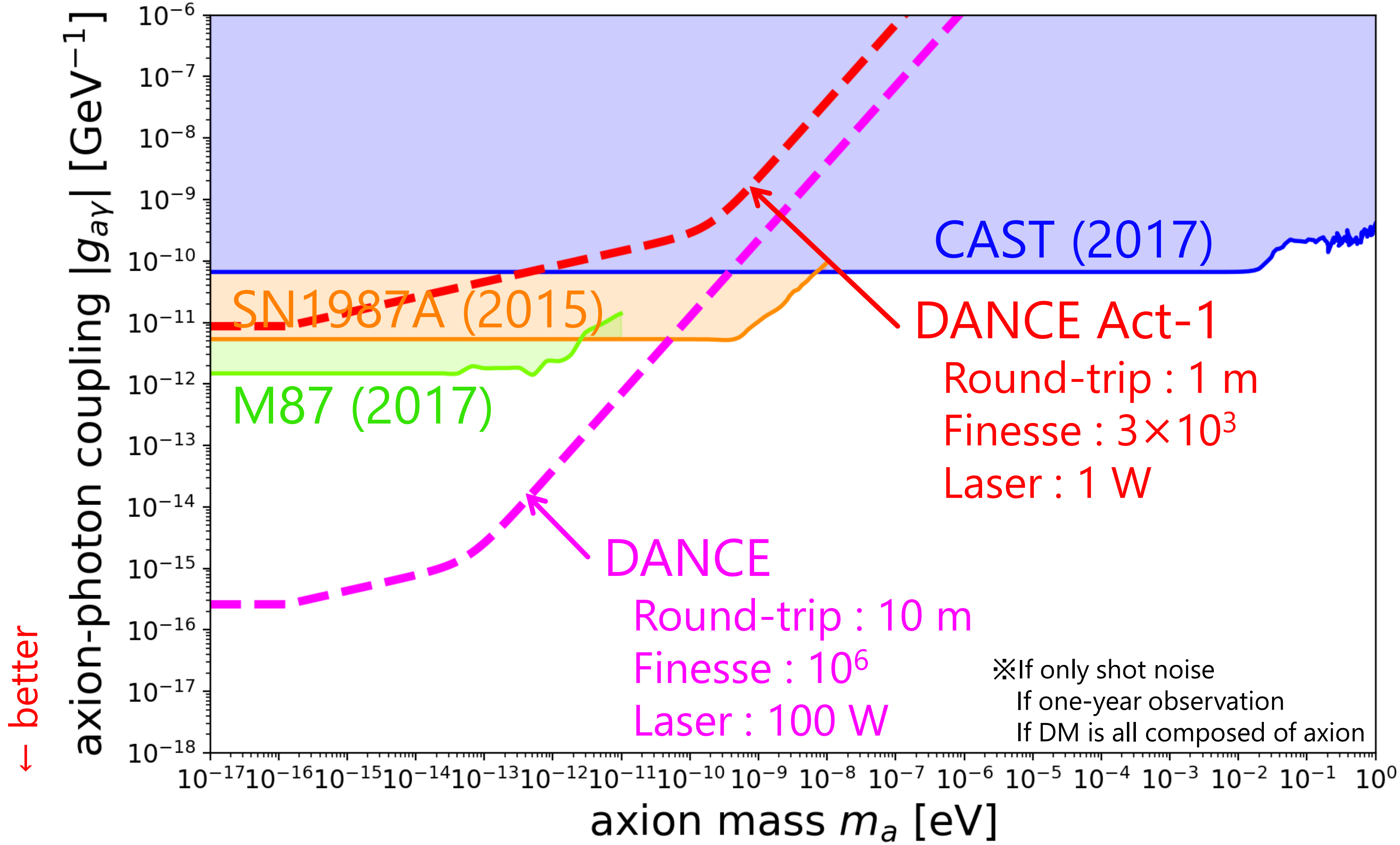
# Bow-tie ring cavity

- Rotated direction is inverted in a linear cavity
  → Rotation effect is cancelled out



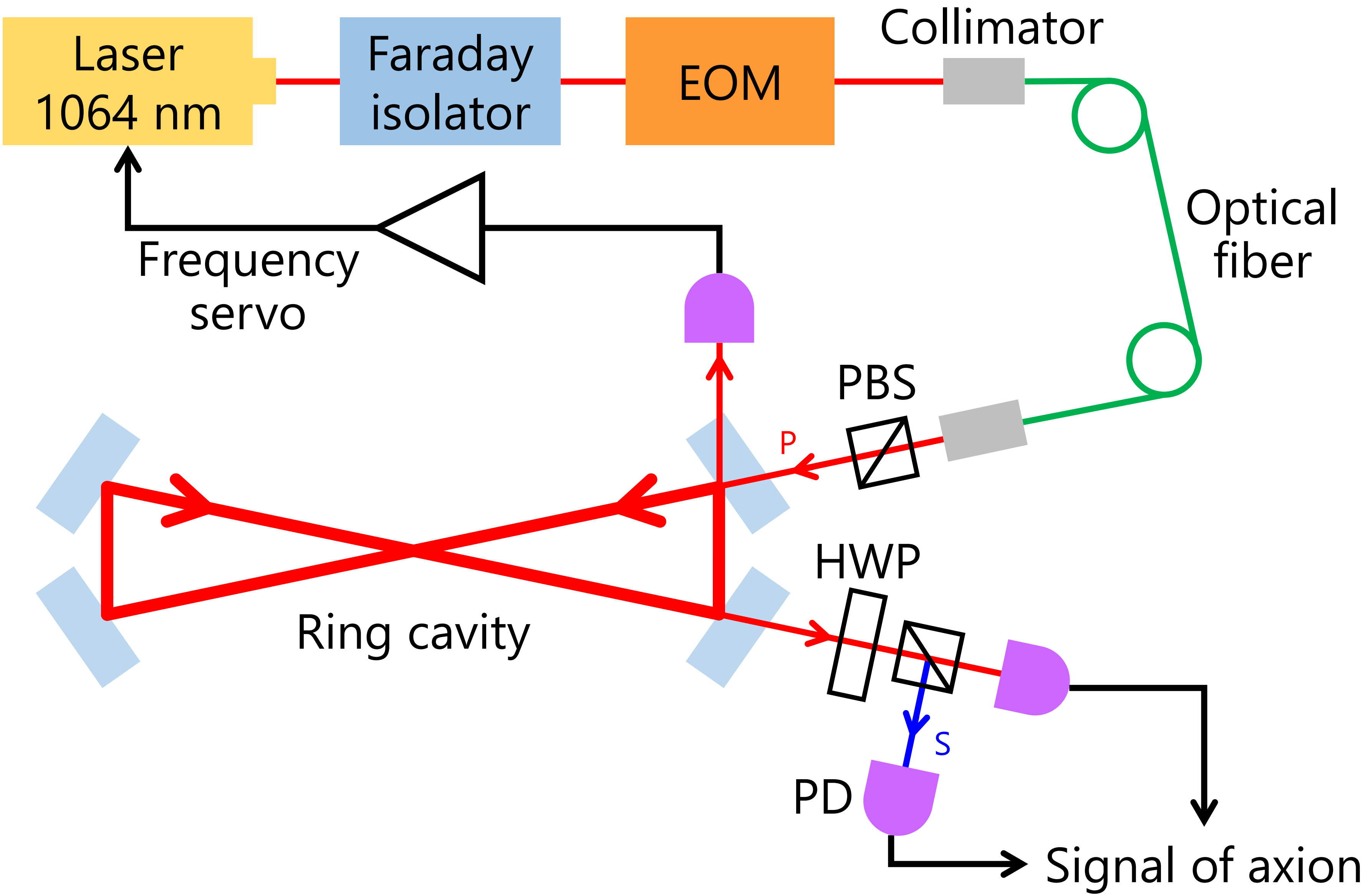

- A bow-tie ring cavity prevents linear polarization from inverting rotated direction


# Sensitivity of DANCE



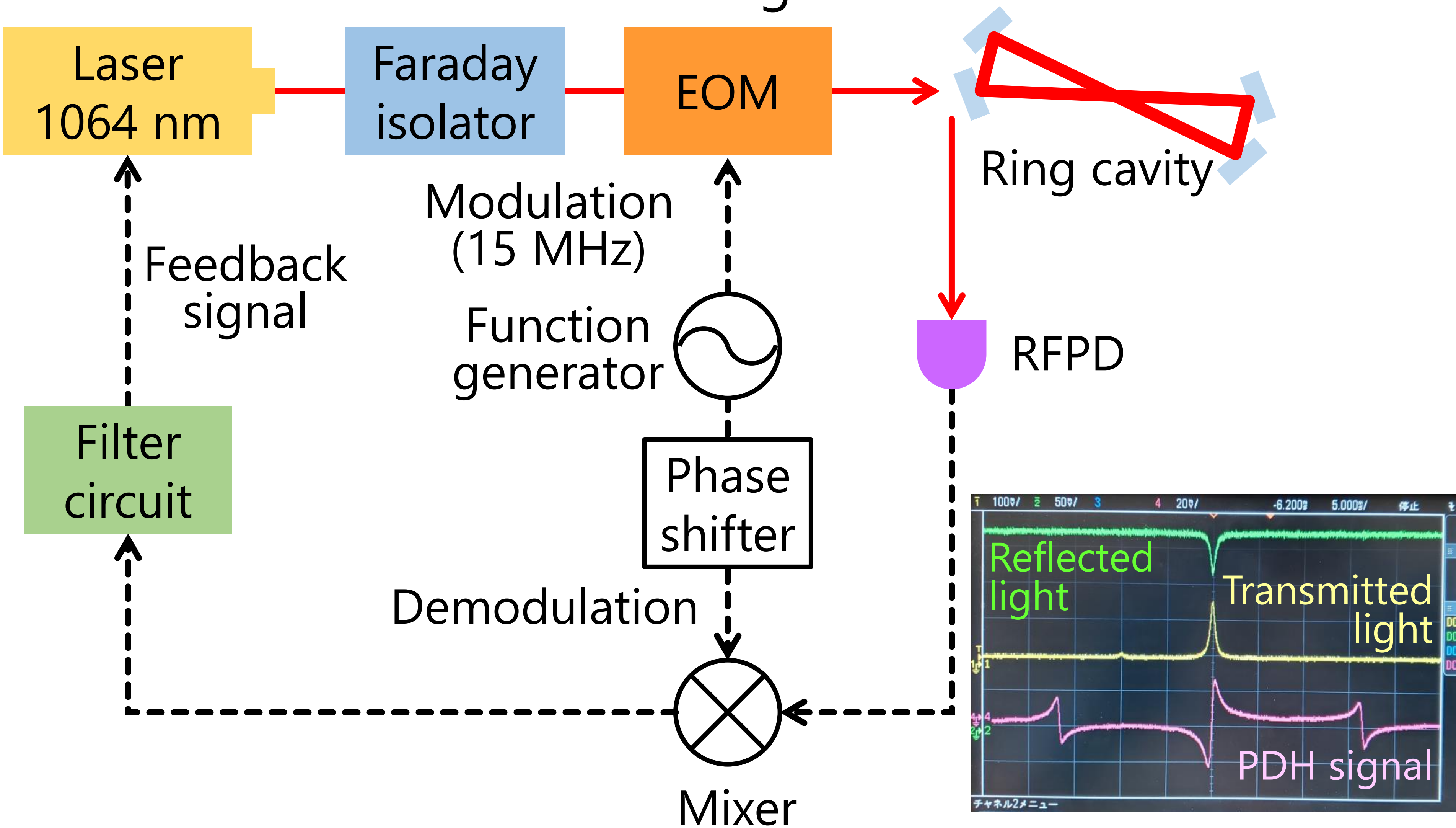

- Shot noise is caused by fluctuations of number of photons
- Need to minimize other noise, except for shot noise

# Experimental setups of DANCE

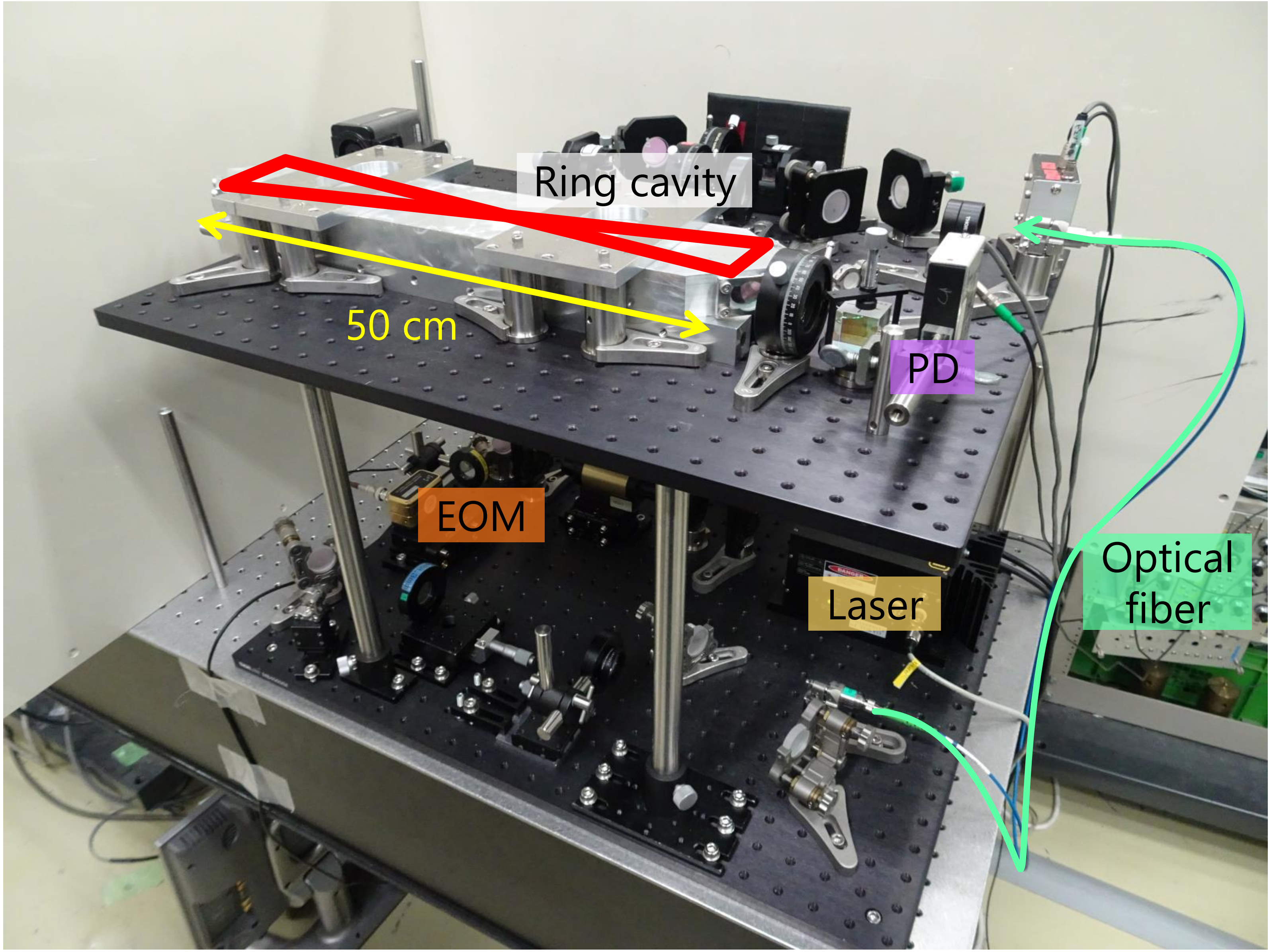


# Frequency servo by PDH technique

- Lock laser frequency to resonance of a cavity to obtain data for a long time



# Picture of the setups (whole)



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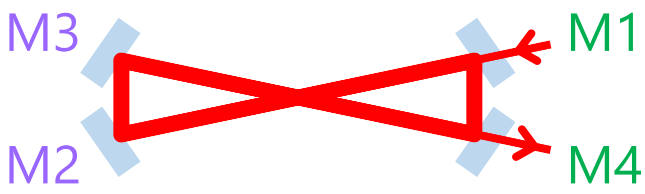
# Performance evaluation of a cavity

| | Design value | Measured value (P polarization) |
|---|---|---|
| Reflectance of mirrors | M1, M4: 99.9 %<br>M2, M3: 100 % | M1, M4: 99.9 %<br>M2, M3: 99.95 % |
| Finesse (Number of round-trips) | 3140 | 525 ± 19<br>(S pol. : 527 ± 29) |
| Round-trip length | 99.4 cm | 102 ± 4 cm |
| Radius of curvature of mirrors | 100 cm (all) | 102 ± 2 cm |
| Incident angle | 42 deg | 41.9 ± 1.7 deg |
| Mode matching ratio | 99.9987 % | 83.03 ± 0.09 % |
| Input power | ~1 W | ~40 mW |

→ Finesse 2100

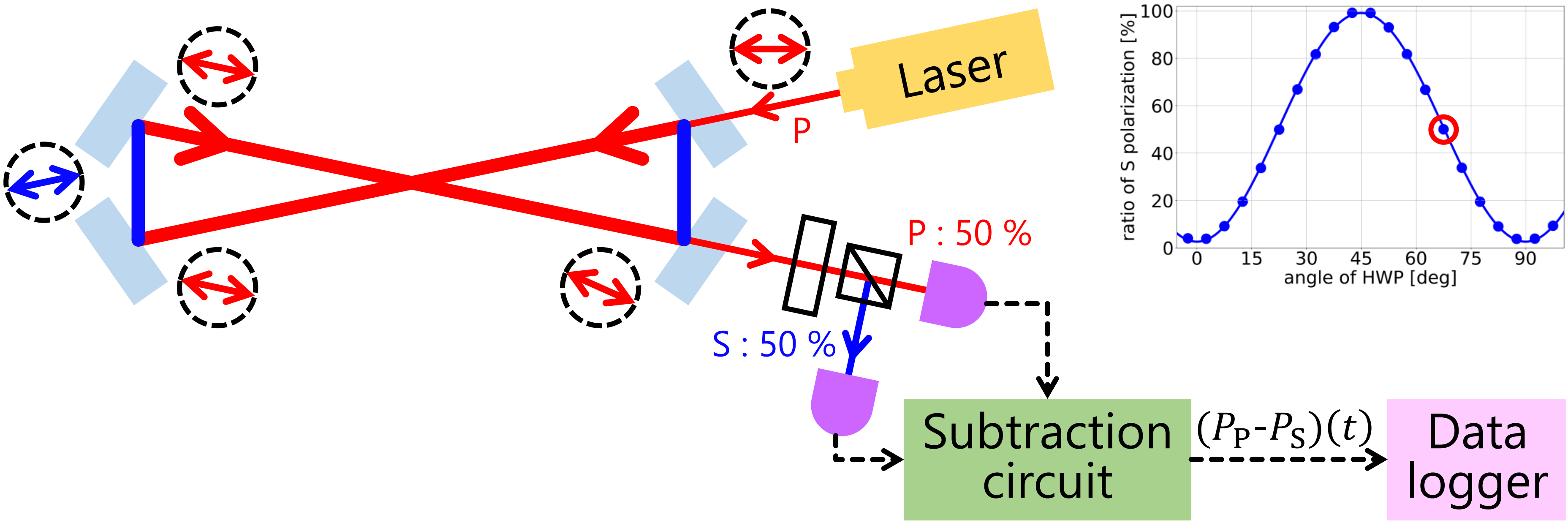
→ Loss of light 0.91 %

→ Misalignment 0.9 deg




- The sensitivity depends on finesse and input power

# Data acquisition

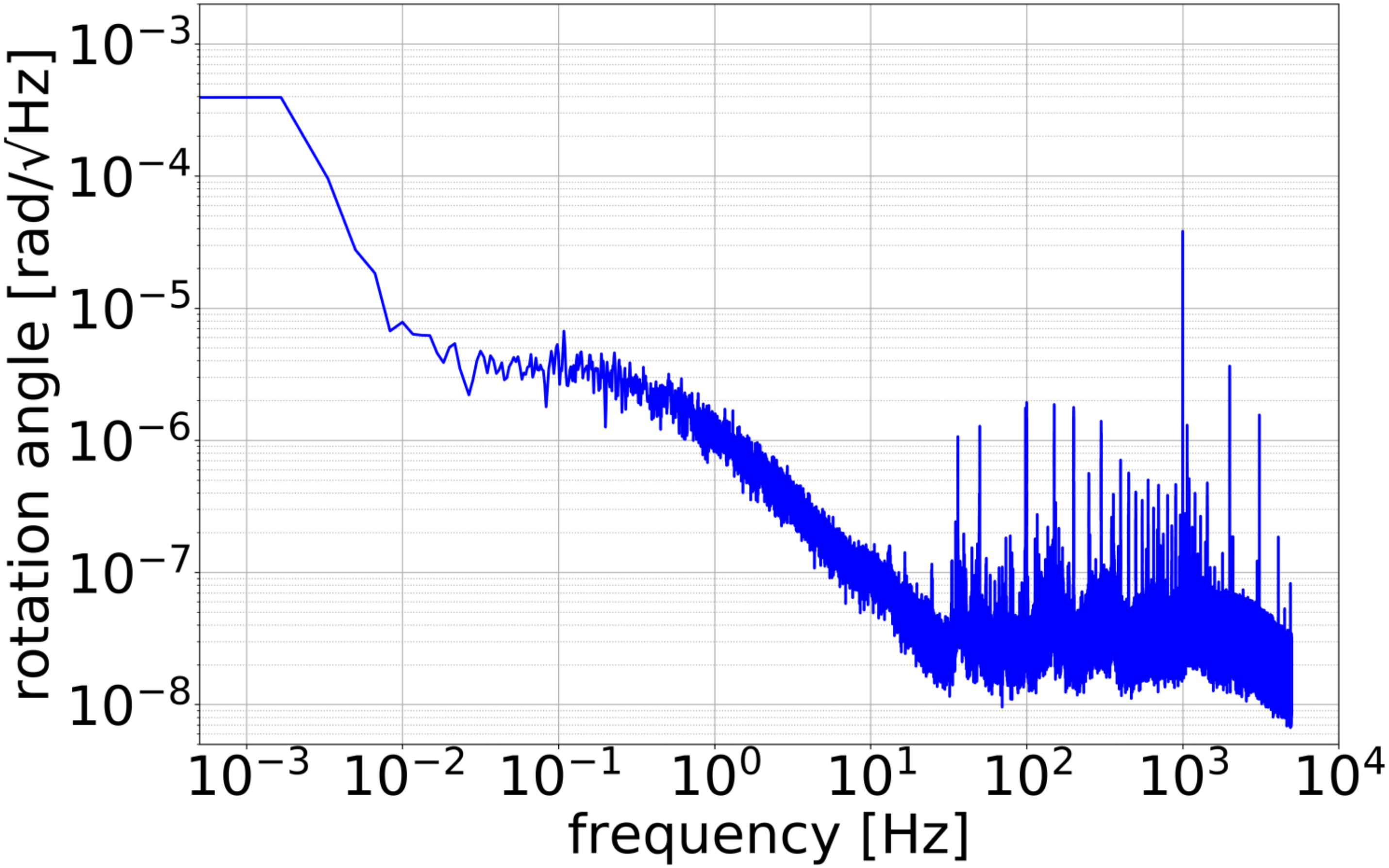



- HWP is fixed to make equal amount of P and S polarization
- Record a differential power $(P_P\text{-}P_S)(t)$
- Use a subtraction circuit to remove common noise of P and S polarization and to reduce quantization noise of a data logger

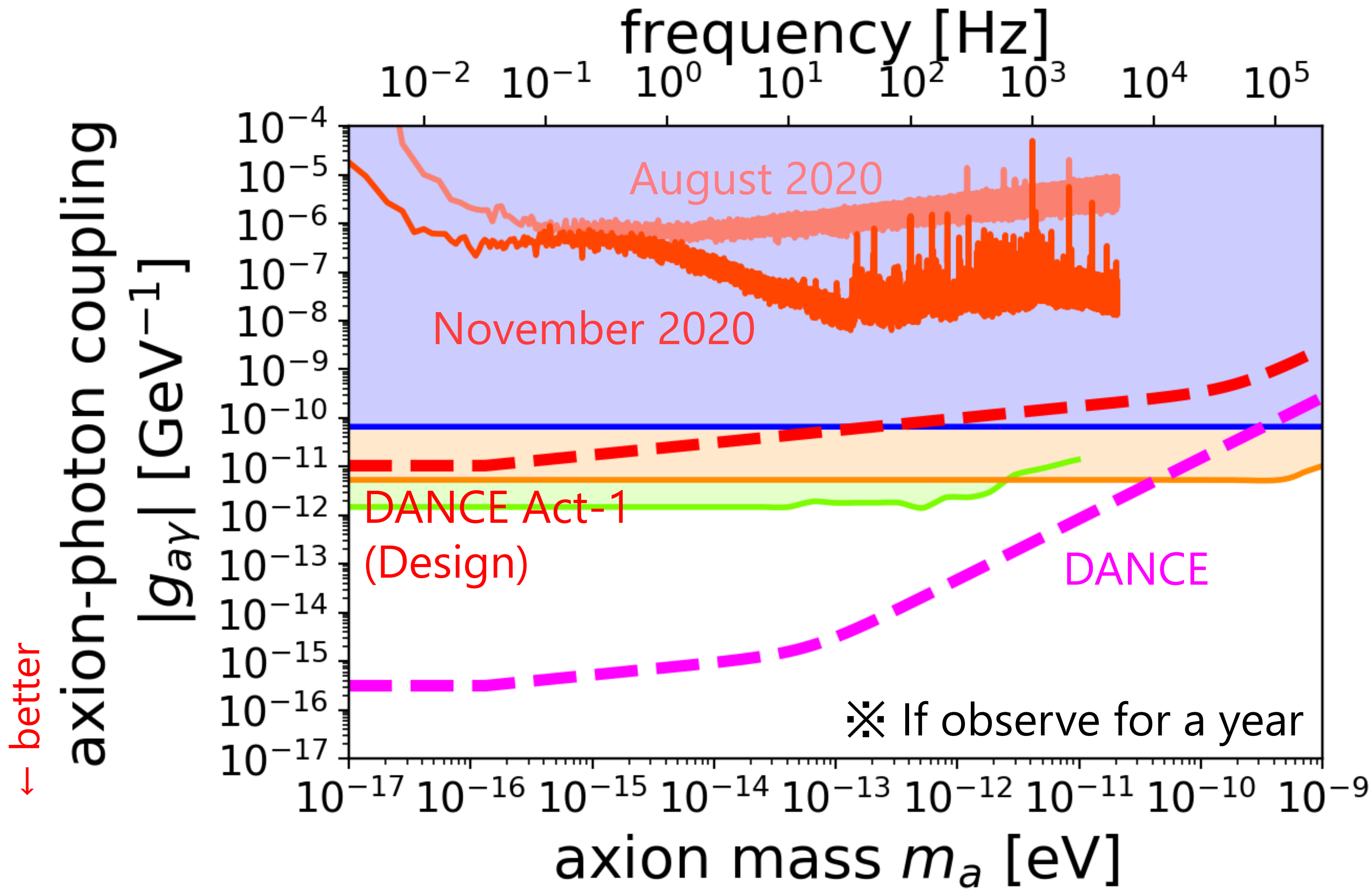
# Data analysis

Rotation angle of linear polarization

$$\phi(t) = \frac{(P_\mathrm{P} - P_\mathrm{S})(t)}{2(P_\mathrm{P} + P_\mathrm{S})}$$



# Current estimated sensitivity




- We have to improve the current sensitivity by $10^3$-$10^5$ times to reach the design sensitivity

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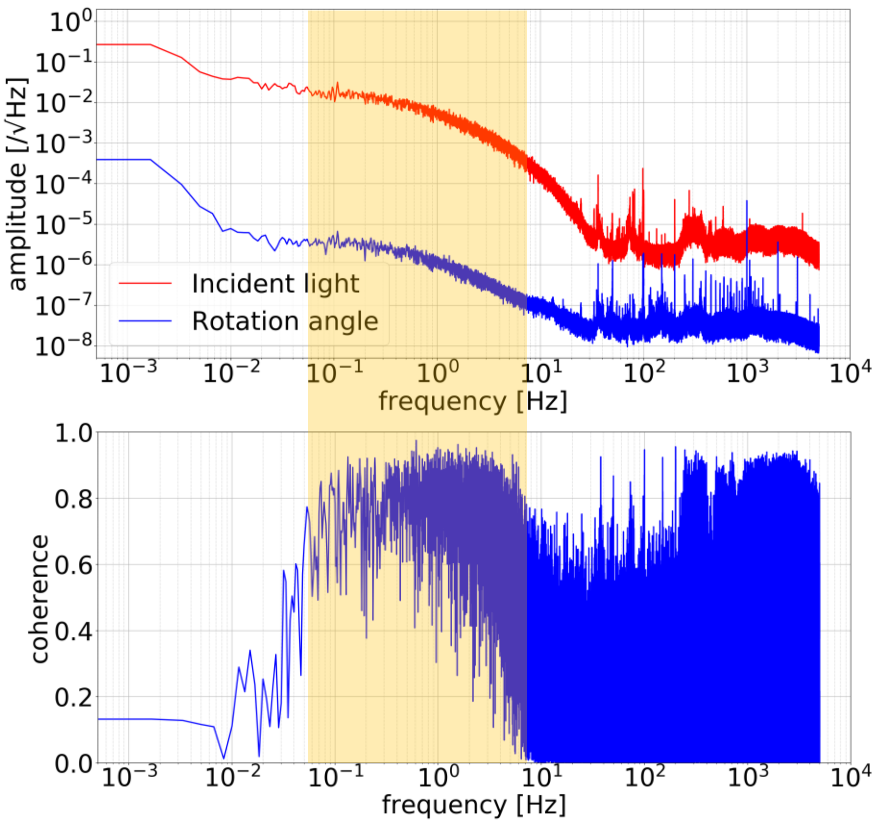
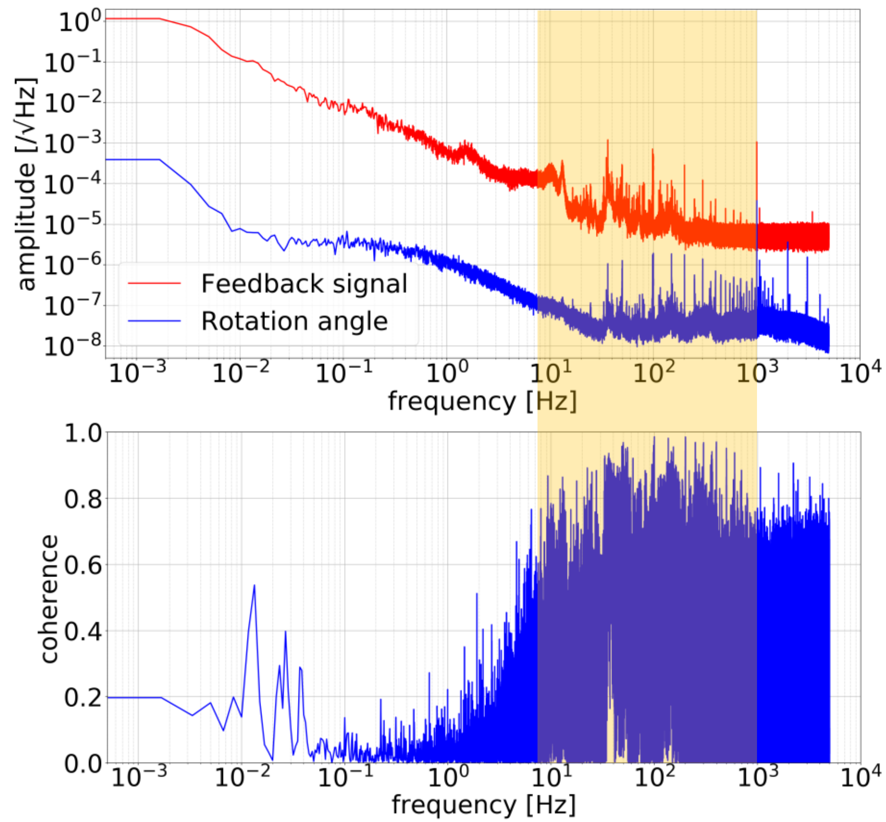
# Discussion for noise

## Correlation with incident light



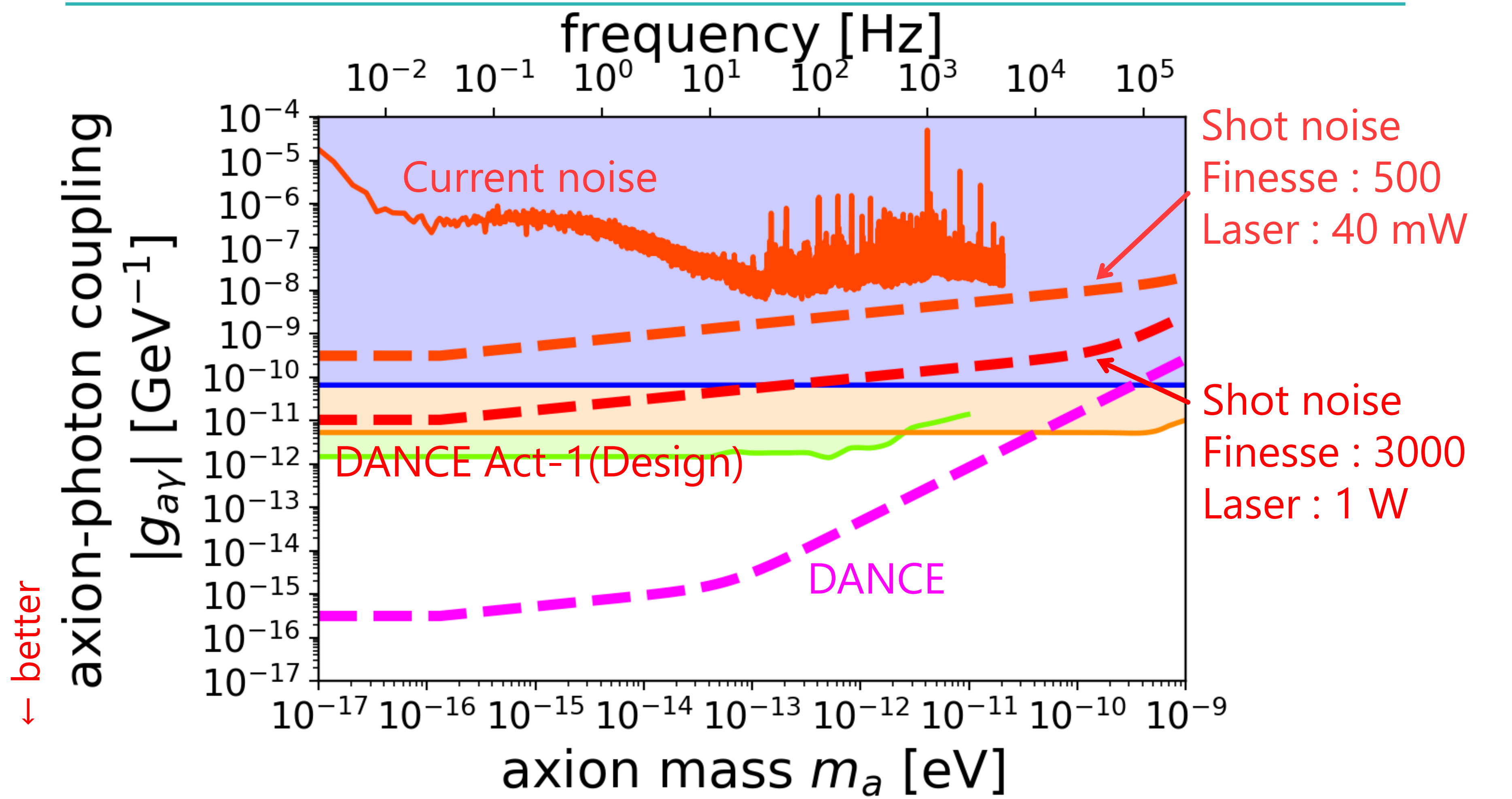

- Sensitivity is limited by laser intensity noise in 0.1 Hz-10 Hz
  - An optical fiber

## Correlation with feedback signal




- Sensitivity is limited by external noise in 10 Hz-1 kHz
  - Vibration (seismic, sounds, mechanical)

# Estimation of sensitivity improvement




- Shot noise limited : +$10^1$-$10^3$ times
- Finesse (500 → 3000) : +10 times
- Laser (40 mW → 1 W) : +10 times

# Future plans

- Improve finesse
  - Change to high quality mirrors
  - Improve alignment of mirrors

- Reduce noise
  - Construct setups without an optical fiber
  - Reduce external vibration

- Higher laser input power

# Summary

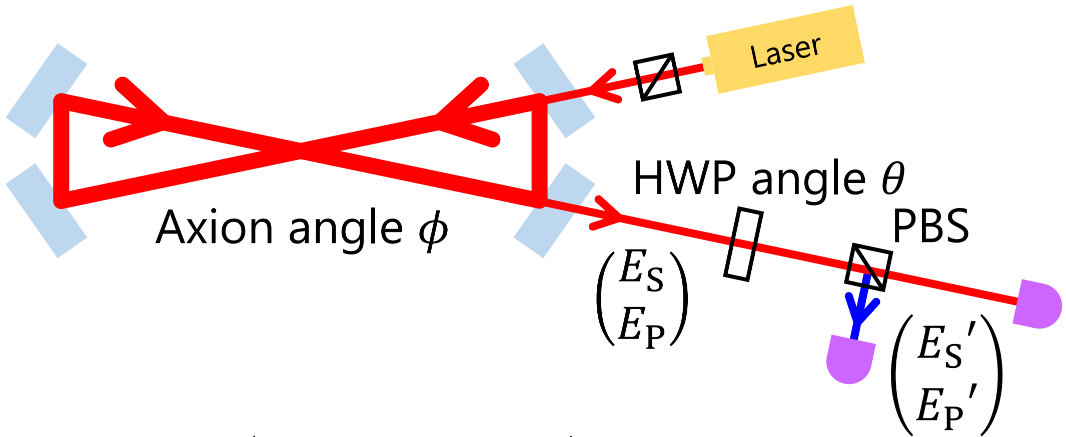
- A new table-top experiment searches for ALPs with a ring cavity
  DANCE: Dark matter Axion search with riNg Cavity Experiment

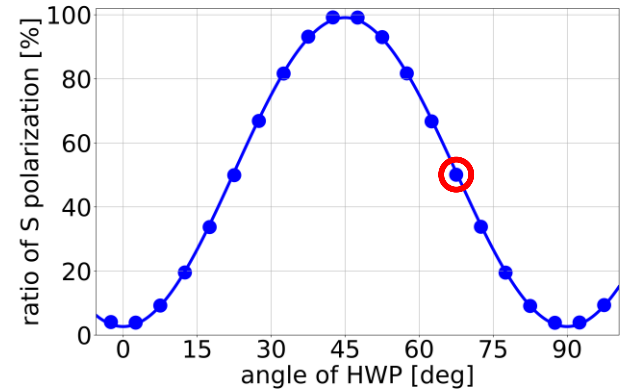
- DANCE observes rotation of linear polarization in a bow-tie cavity

- Prototype experiment DANCE Act-1 is ongoing
  - Assembly of optics and performance evaluation of a cavity are finished
  - Now hunting and reducing noise to achieve the design sensitivity

# Extra Slides

# Data analysis




$$\begin{pmatrix} E_S \\ E_P \end{pmatrix} = \begin{pmatrix} E_0 \sin \phi(t) \\ E_0 \cos \phi(t) \end{pmatrix}, \text{ HWP } \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix}$$

$$\rightarrow \begin{pmatrix} E_S{}' \\ E_P{}' \end{pmatrix} = \begin{pmatrix} E_0 \sin(2\theta + \phi(t)) \\ E_0 \cos(2\theta + \phi(t)) \end{pmatrix}$$

$$P_S = {E_S'}^2 = E_0^2 \sin^2(2\theta + \phi(t))$$
$$P_P = {E_P'}^2 = E_0^2 \cos^2(2\theta + \phi(t))$$

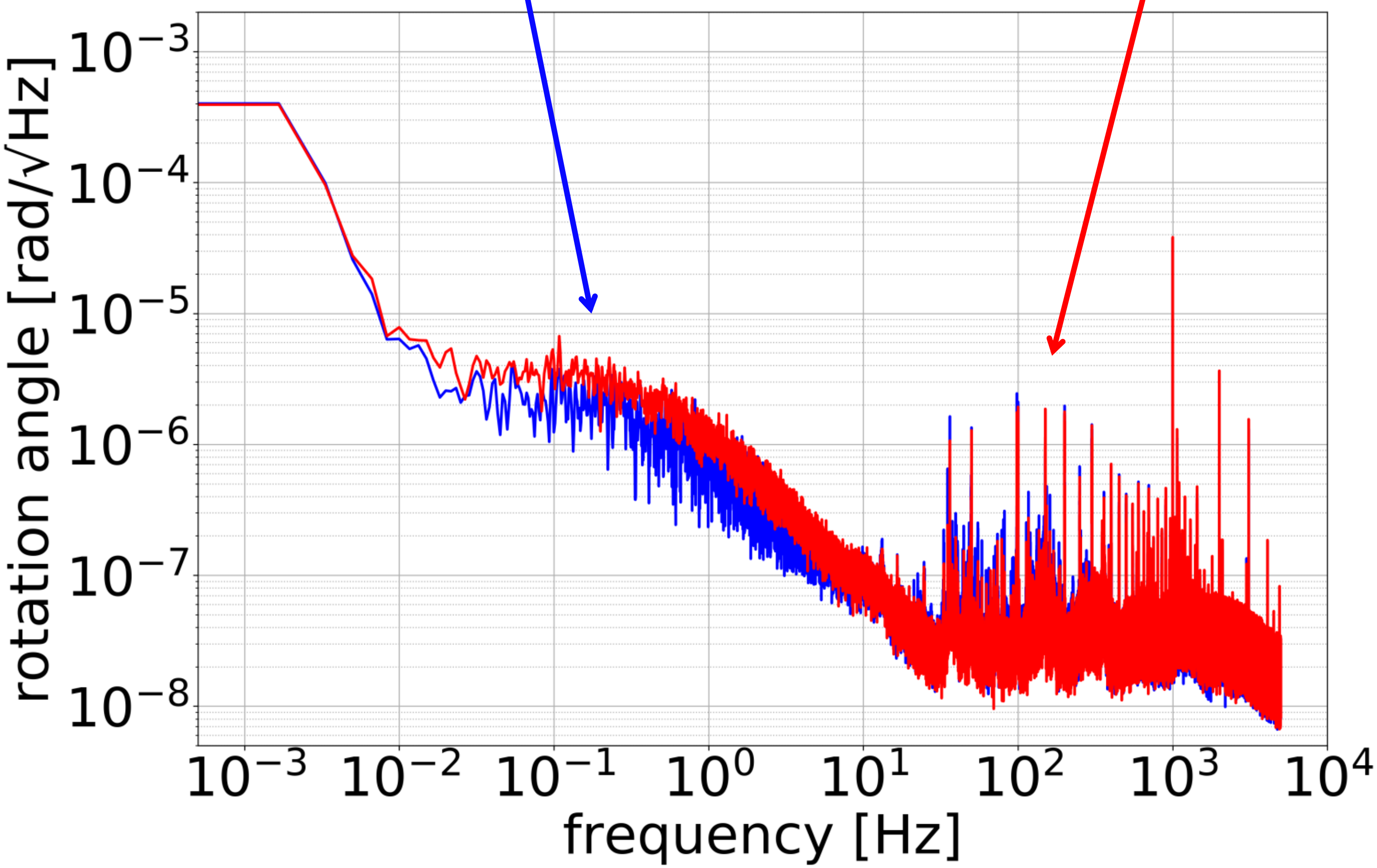
Differential : $P_P - P_S = E_0^2 \cos(2(2\theta + \phi(t)))$

When HWP angle $2\theta = 45$ deg, $P_P - P_S = 2E_0^2 \phi(t)$

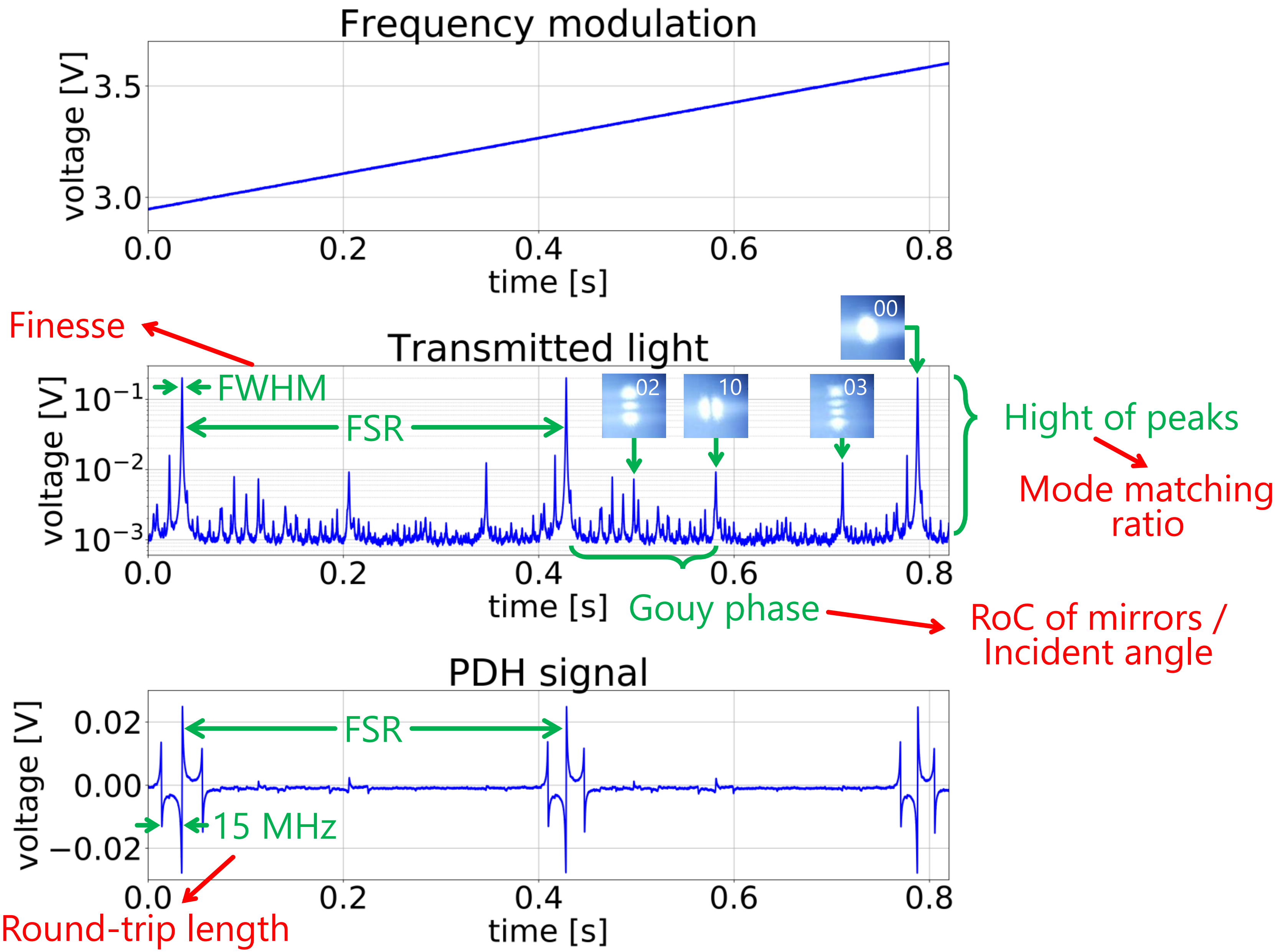
# Comparison for data analysis

$$\phi(t) = \frac{(P_\mathrm{P} - P_\mathrm{S})(t)}{2(P_\mathrm{P}(t) + P_\mathrm{S}(t))}$$

$$\phi(t) = \frac{(P_\mathrm{P} - P_\mathrm{S})(t)}{2(\overline{P_\mathrm{P} + P_\mathrm{S}})}$$



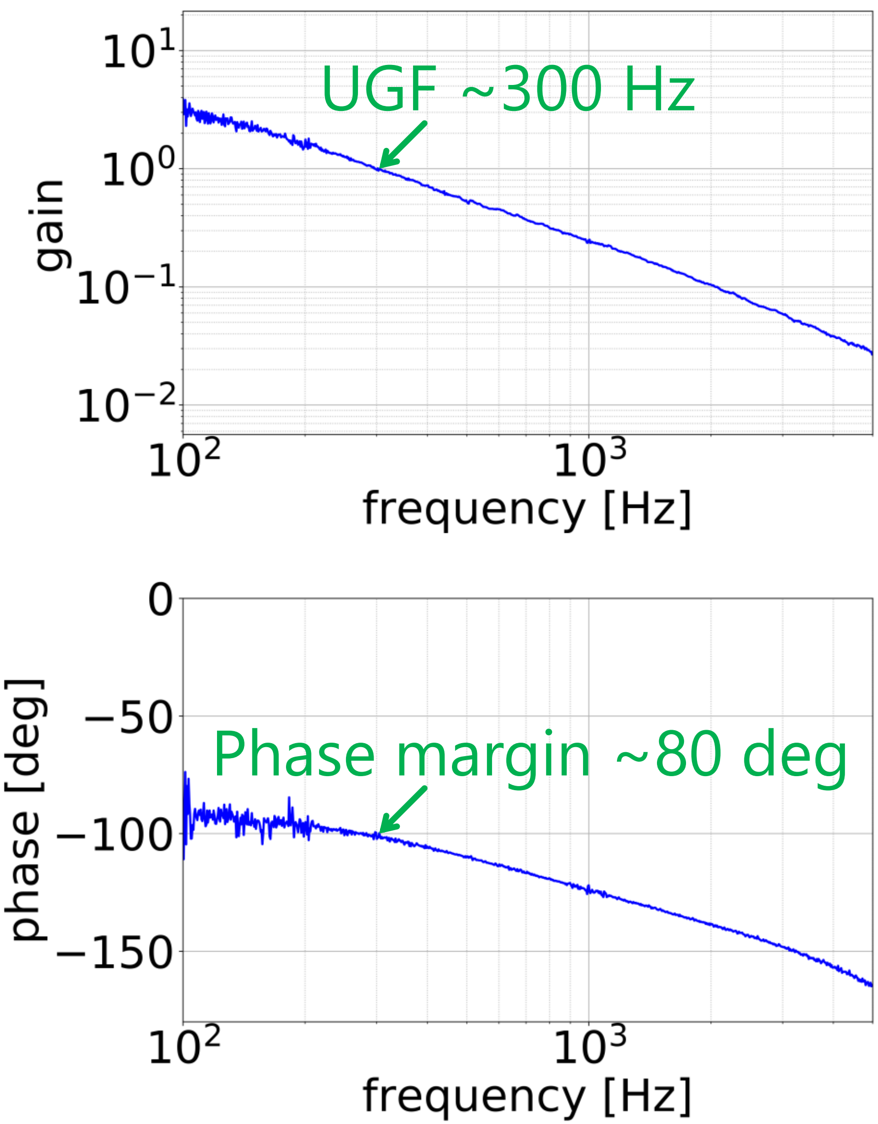
# Cavity scan



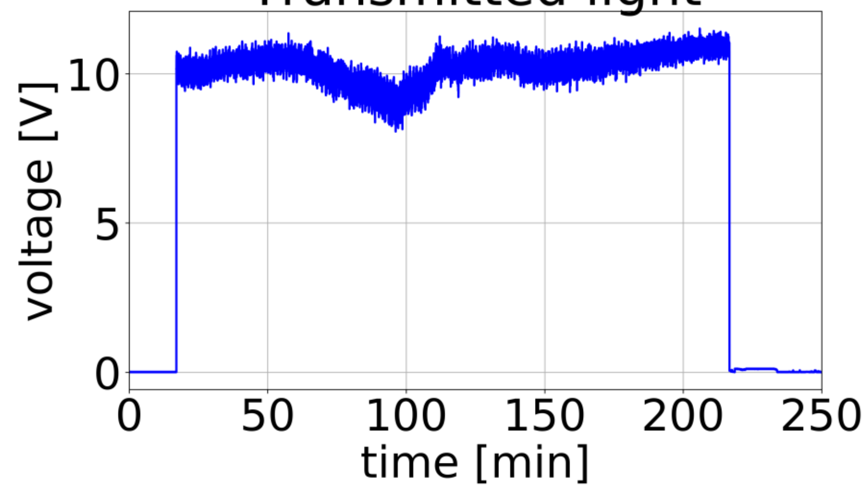
Frequency modulation
voltage [V]
3.5
3.0
0.0
0.2
0.4
0.6
0.8
time [s]
Finesse
Transmitted light
00
02
10
03
FWHM
FSR
$10^{-1}$
$10^{-2}$
$10^{-3}$
Hight of peaks
Mode matching ratio
Gouy phase
RoC of mirrors / Incident angle
PDH signal
0.02
0.00
−0.02
FSR
15 MHz
Round-trip length

# Stability of feedback control

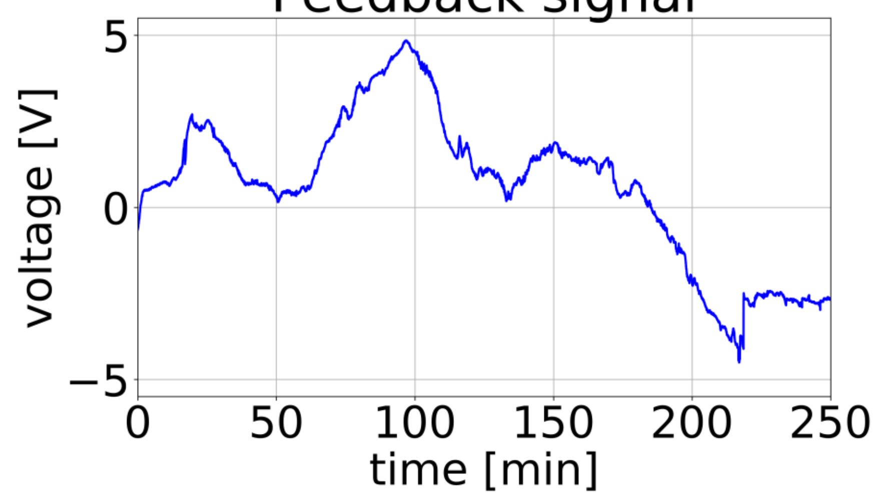
## Open-loop transfer function




## Transmitted light



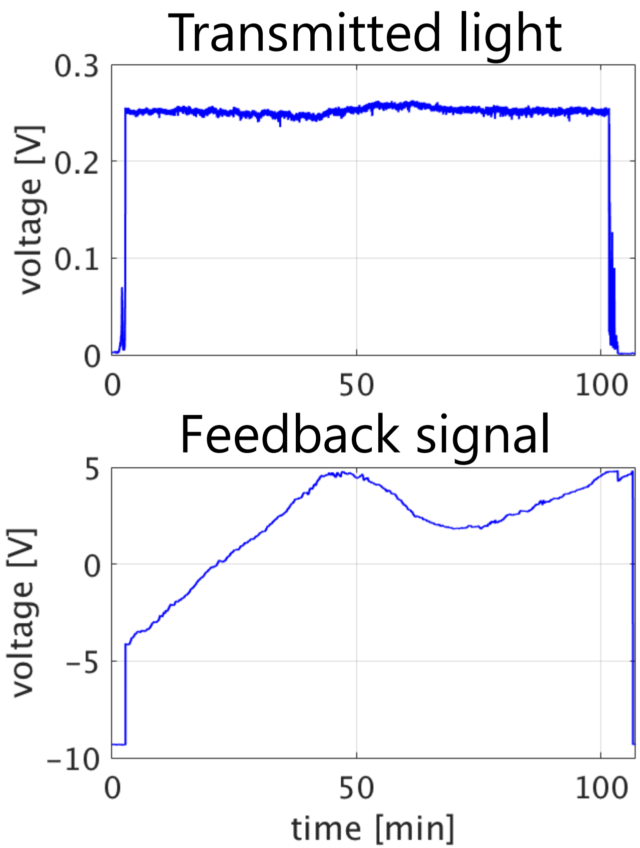

## Feedback signal



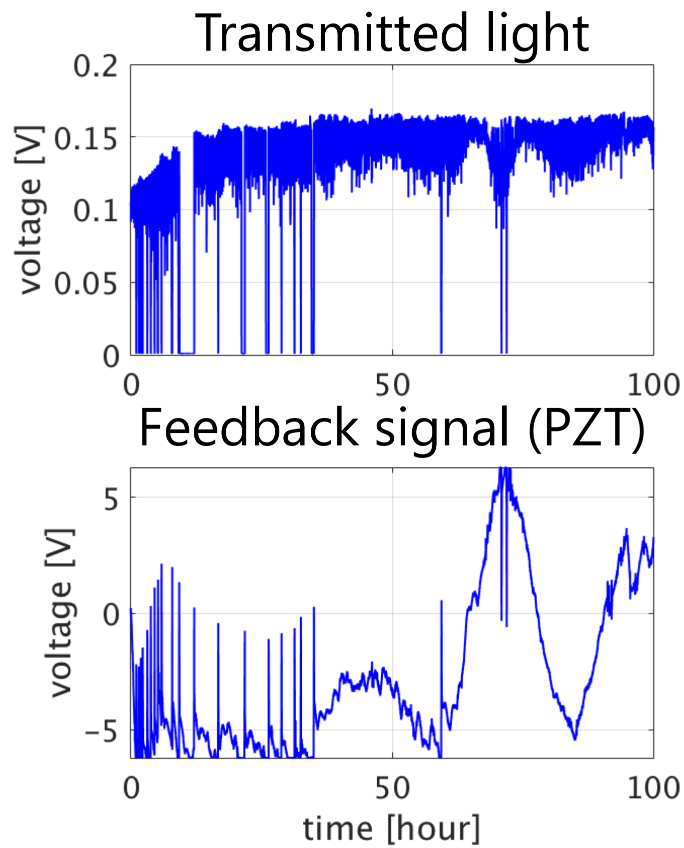

- Control continued in a few hours

# Double-loop control

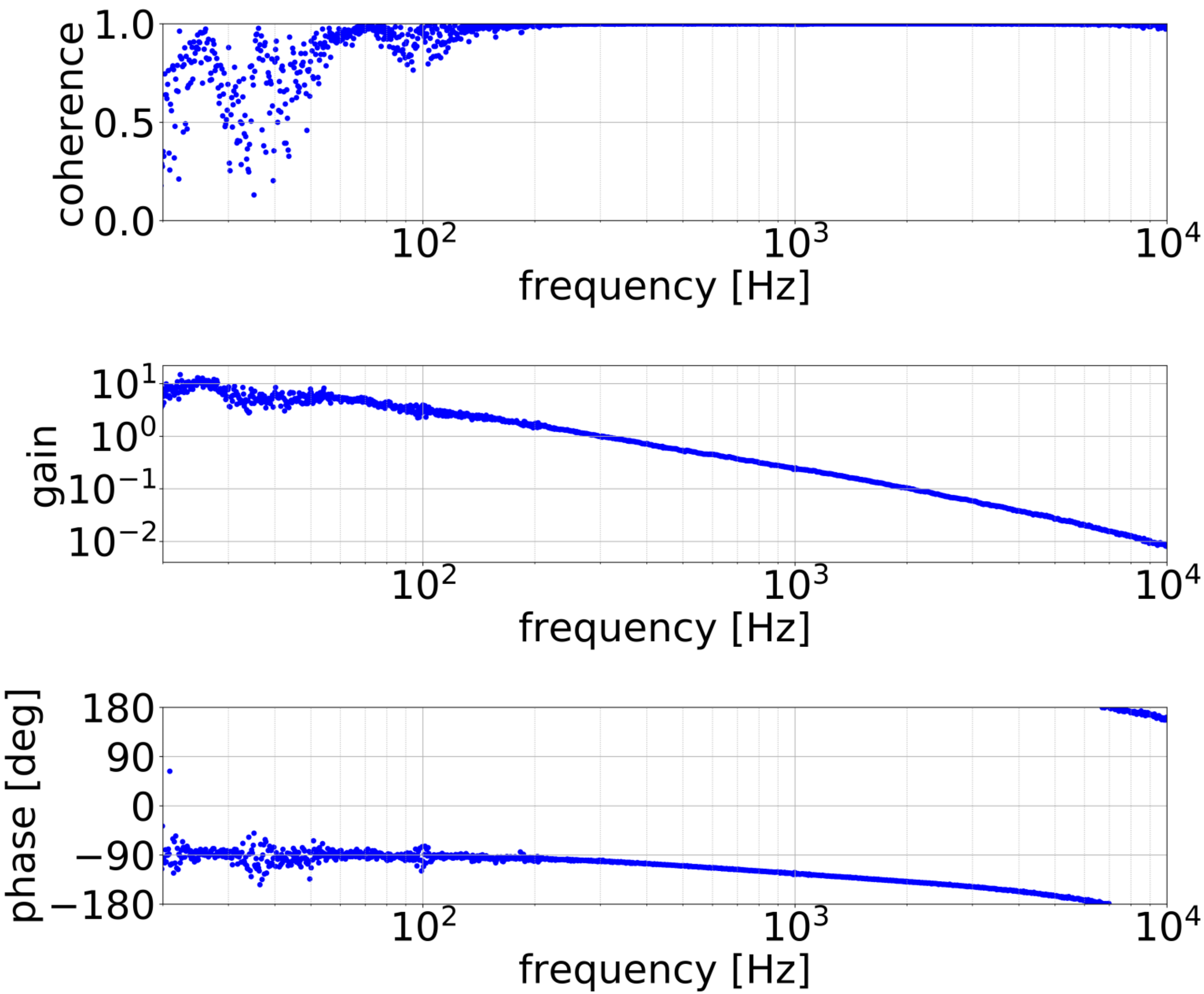
Only with laser PZT actuator
: in a few hours



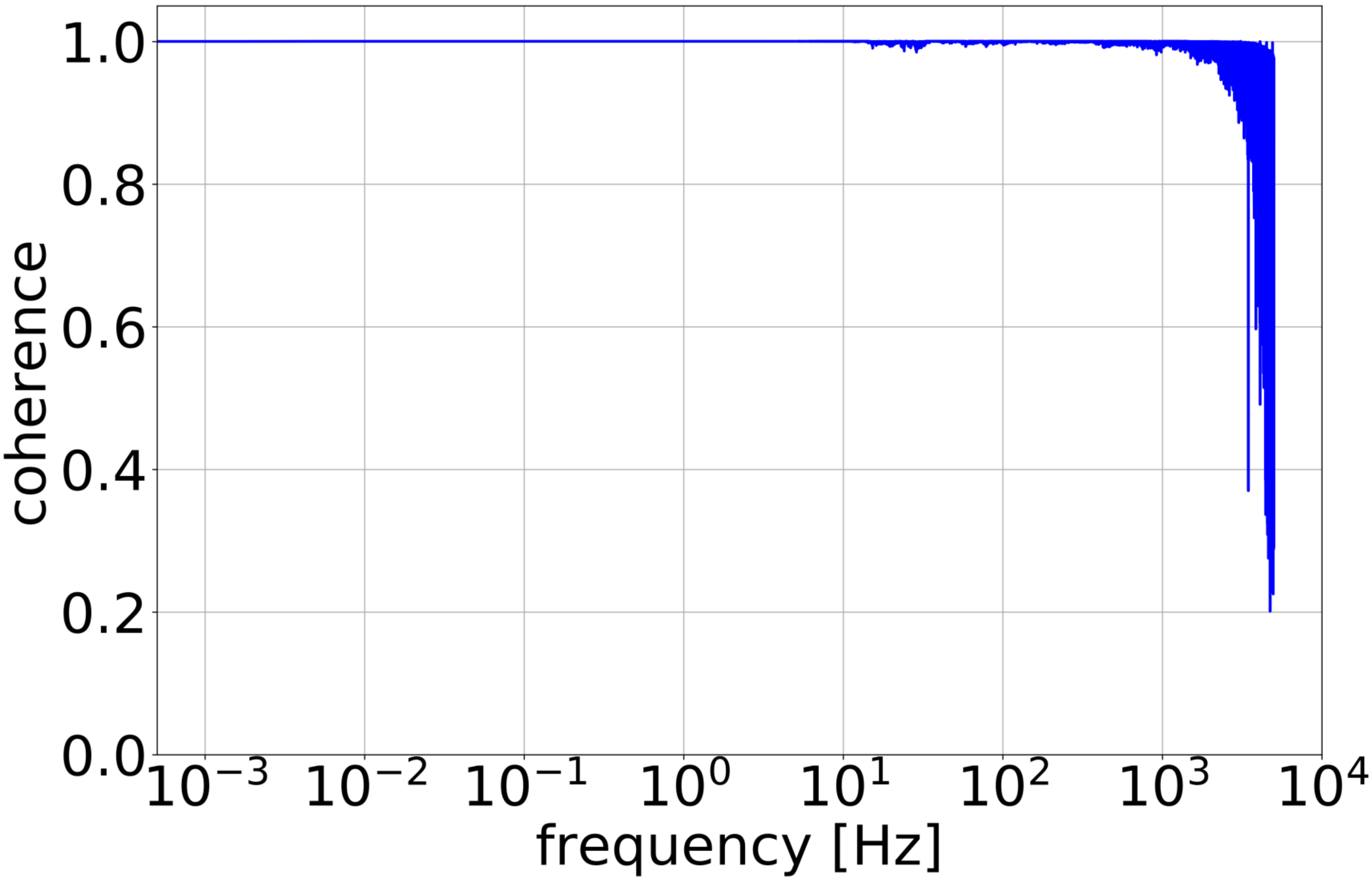

With laser PZT actuator
and temperature actuator
: in a few days



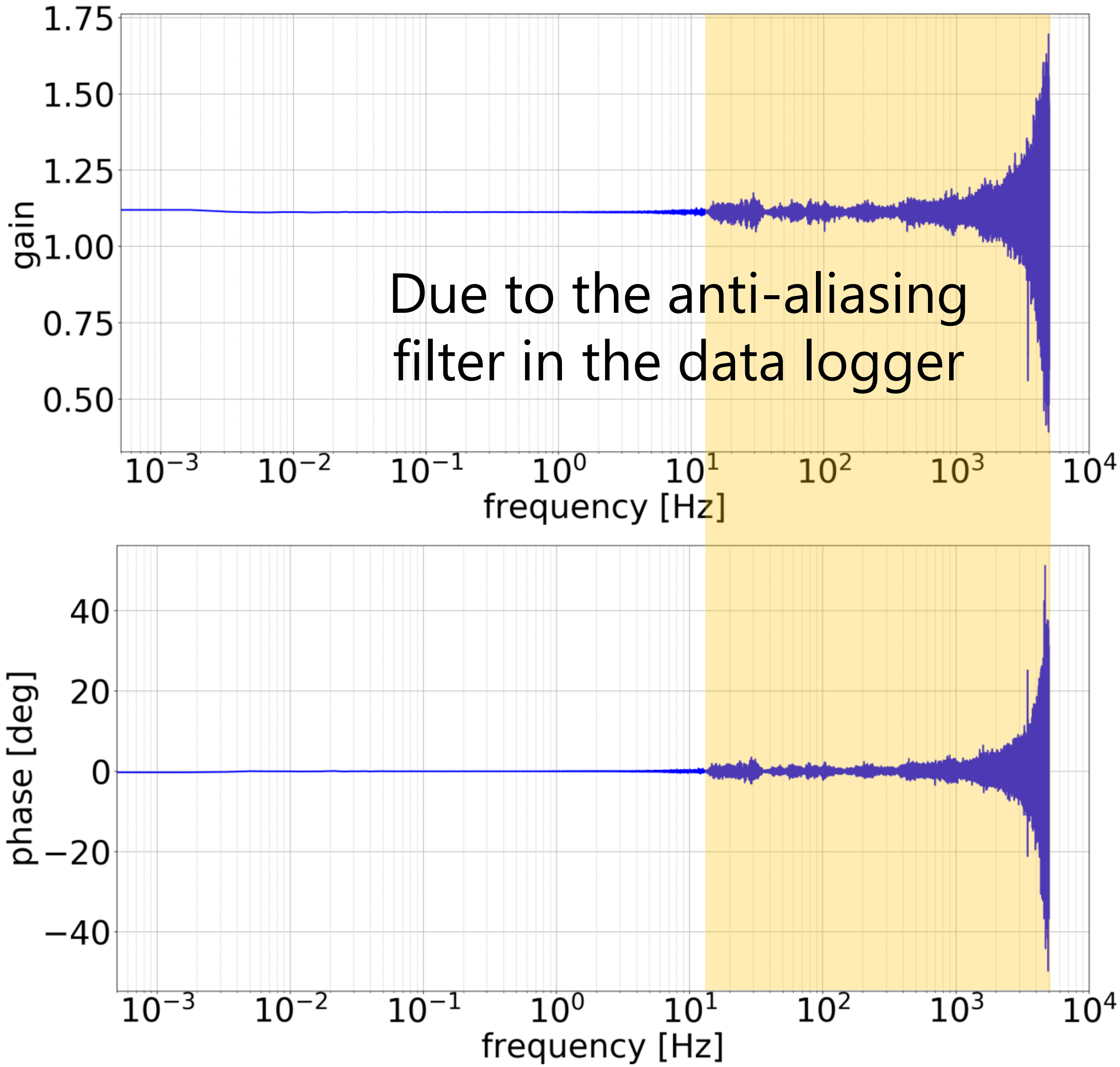
# Open-loop transfer function (raw data)



# Coherence between polarizations



# Transfer function between polarizations

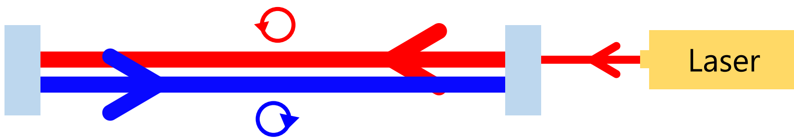


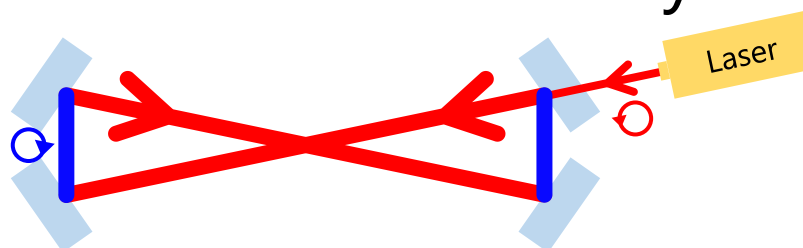
# Bow-tie cavity & Double-pass configuration

- Bow-tie ring cavity

The effect is canceled in a linear cavity

Not canceled in a bow-tie cavity



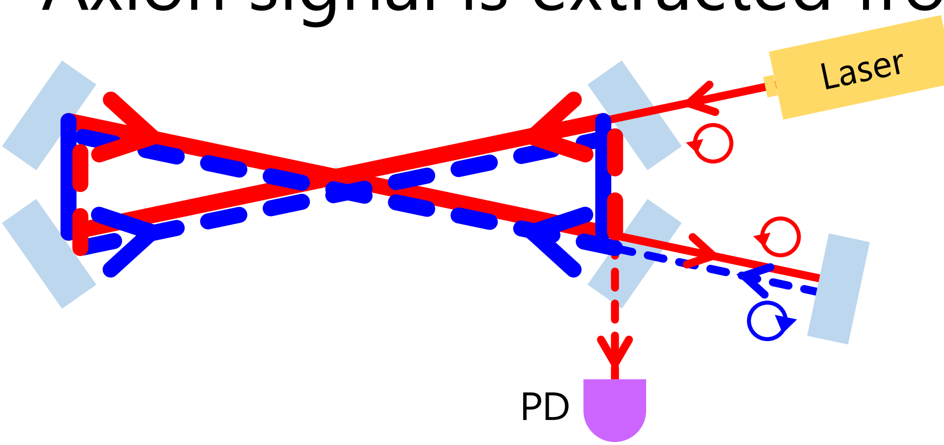




- Double-pass configuration

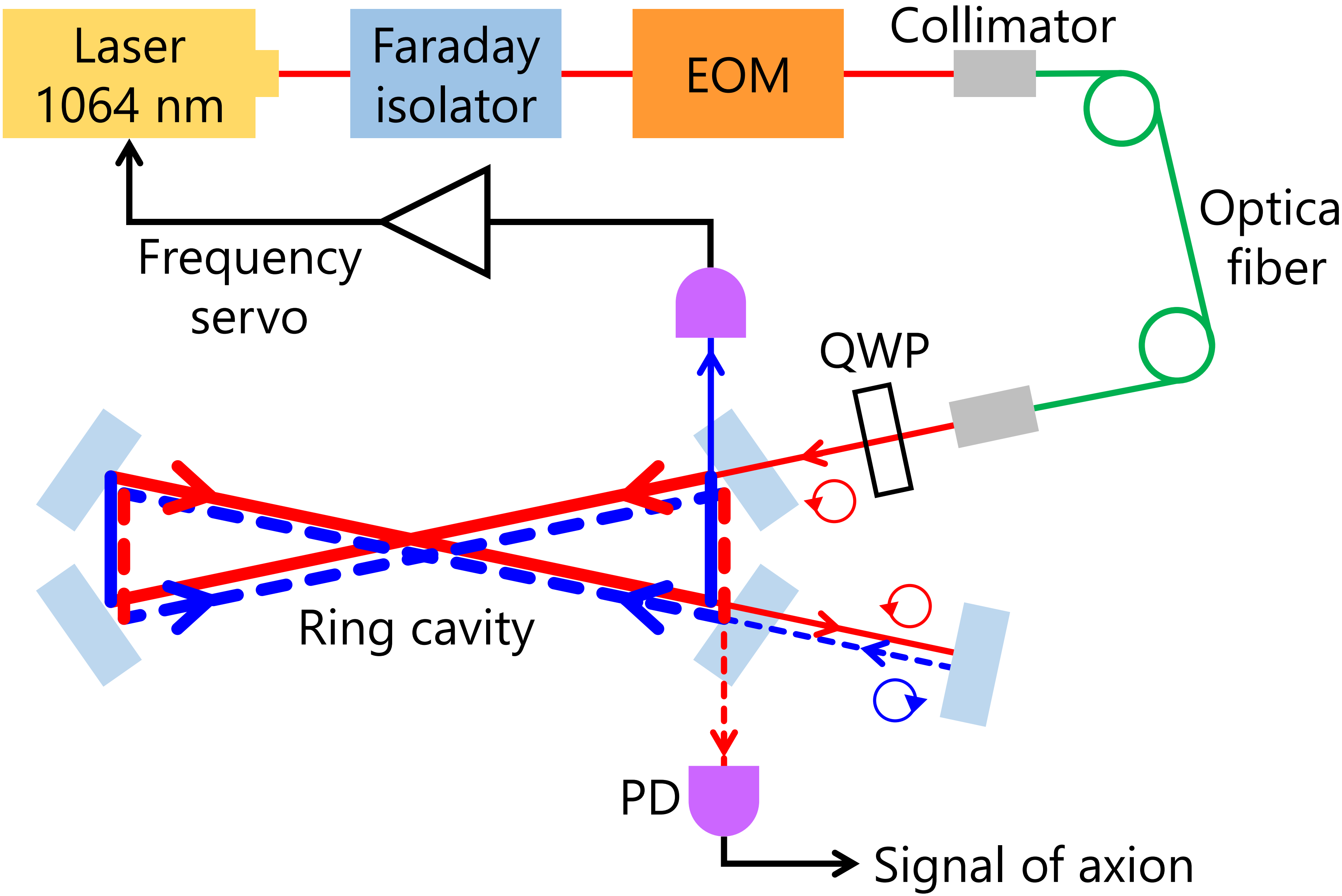
Transmitted beam is reflected back into a cavity

Axion signal is extracted from the reflection

(null measurement)

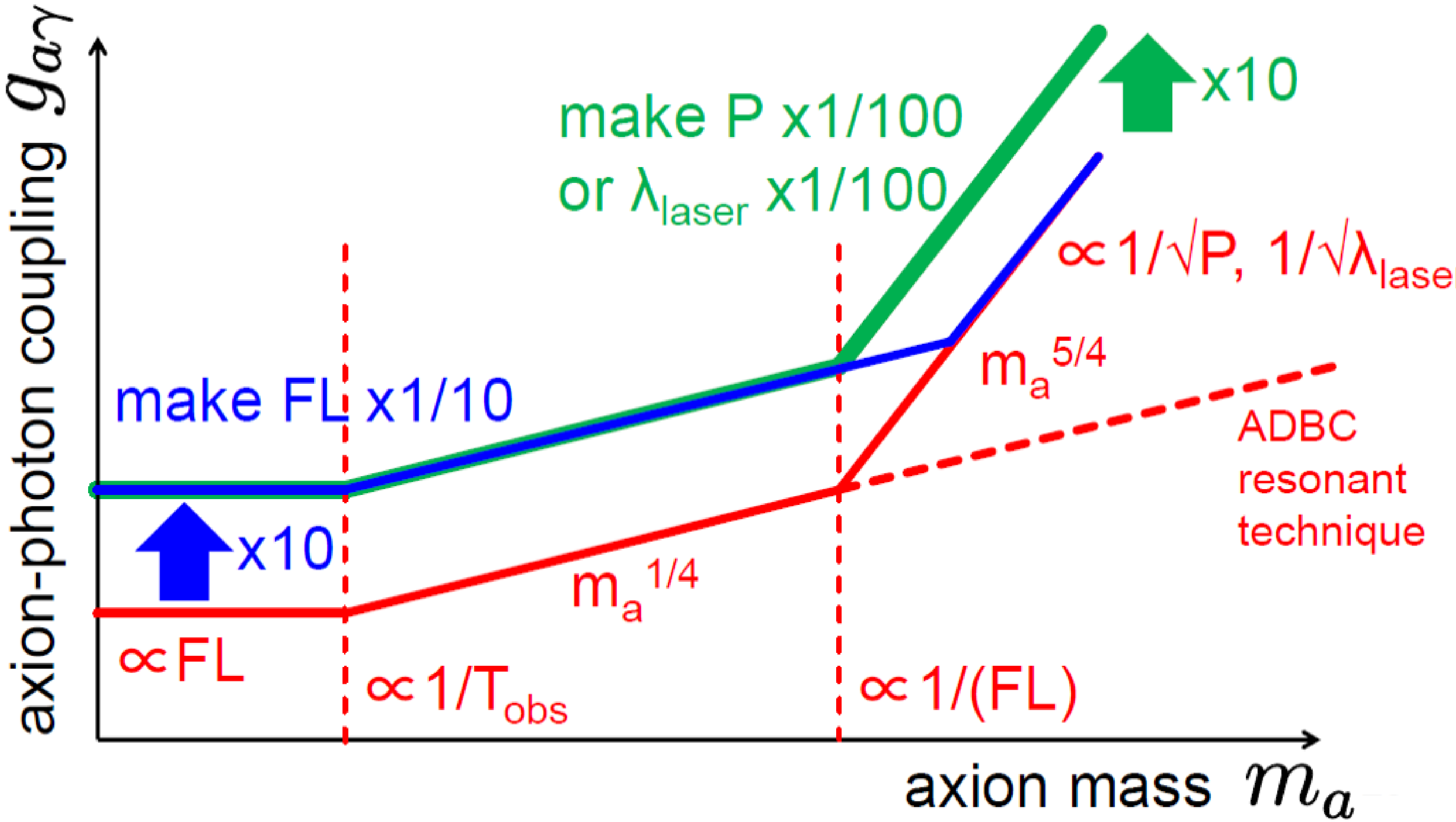


# Setups (Circular pol. & Double-pass)



# Sensitivity Design

- Brute force necessary, you cannot win for free



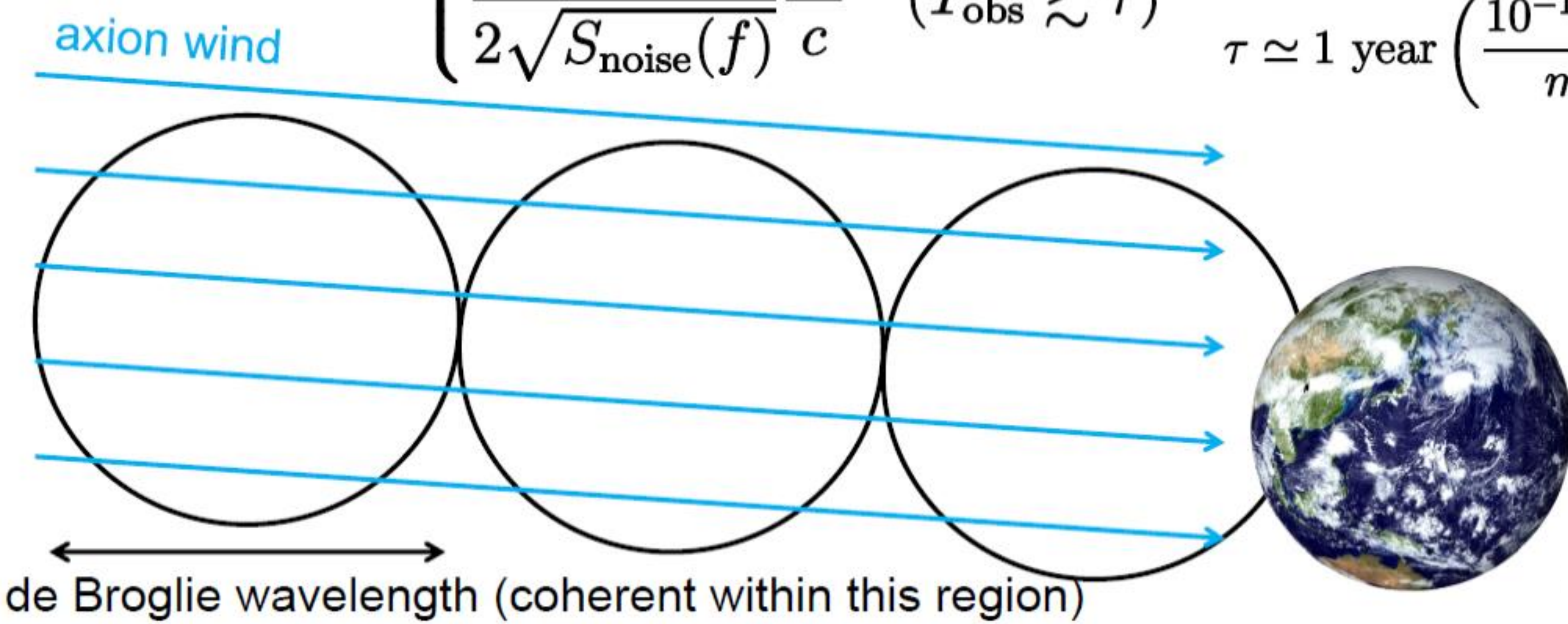
Made by Yuta Michimura

# Coherent Time Scale

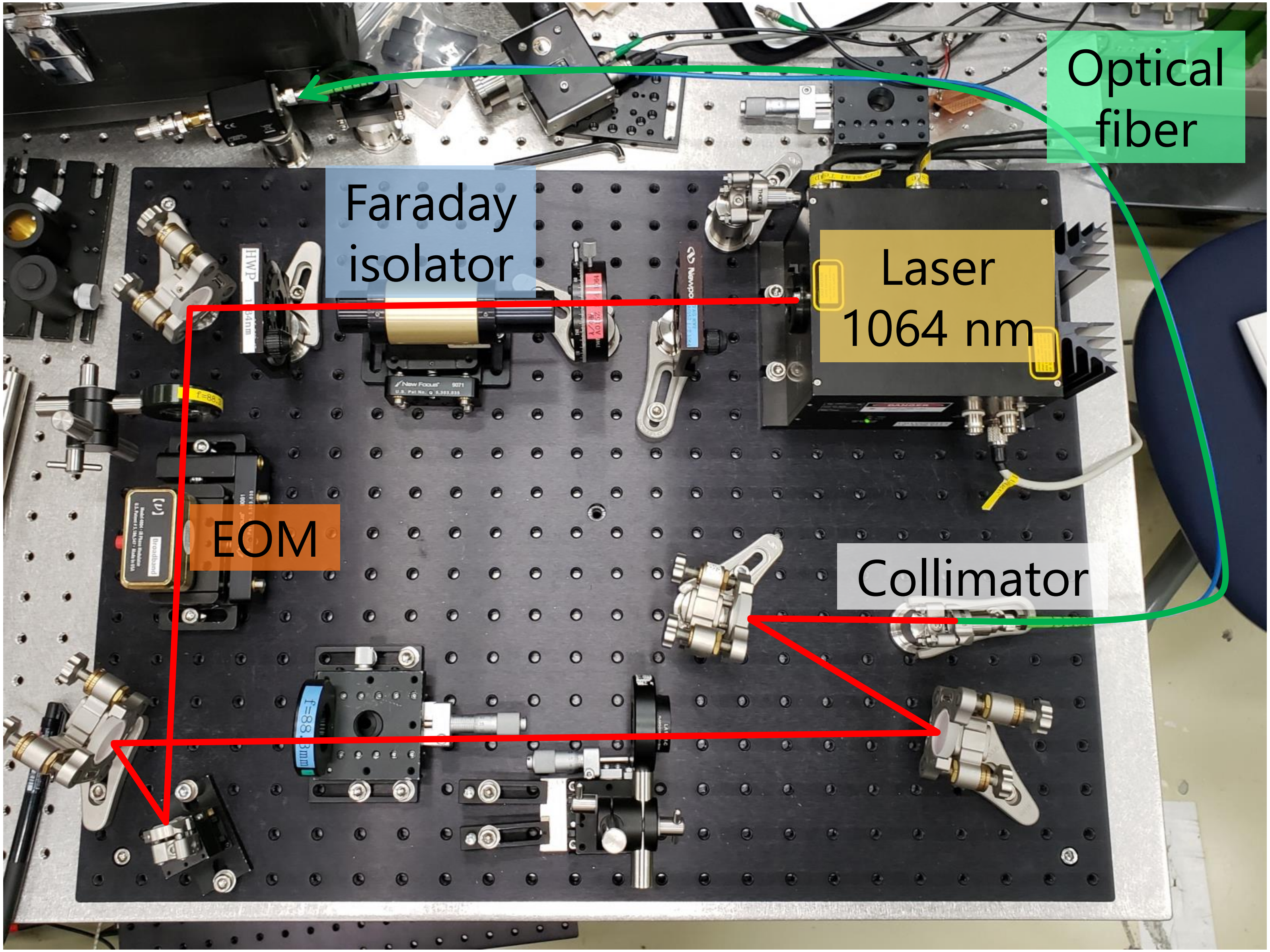
- SNR grows with √Tobs if integration time is shorter than coherent time scale
- SNR grows with (Tobs)$^{1/4}$ if integration time is longer

$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\mathrm{obs}}}}{2\sqrt{S_{\mathrm{noise}}(f)}} \dfrac{\delta c}{c} & (T_{\mathrm{obs}} \lesssim \tau) \\ \dfrac{(T_{\mathrm{obs}}\tau)^{1/4}}{2\sqrt{S_{\mathrm{noise}}(f)}} \dfrac{\delta c}{c} & (T_{\mathrm{obs}} \gtrsim \tau) \end{cases}$$

$$\tau \simeq 1 \text{ year} \left( \frac{10^{-16}\ \mathrm{eV}}{m_a} \right)$$



# Picture of the setups (1st floor)



# Picture of the setups (2nd floor)